Bs Mixing and Lifetime Difference at CDF

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On behalf of the CDF Collaboration

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Outline

- Tevatron and CDF II
- $B_s \to D_s D_s$
- $B_s \to KK$
- $B_s \to J/\psi\varphi$ $\longrightarrow$ β_s

$\Delta\Gamma$

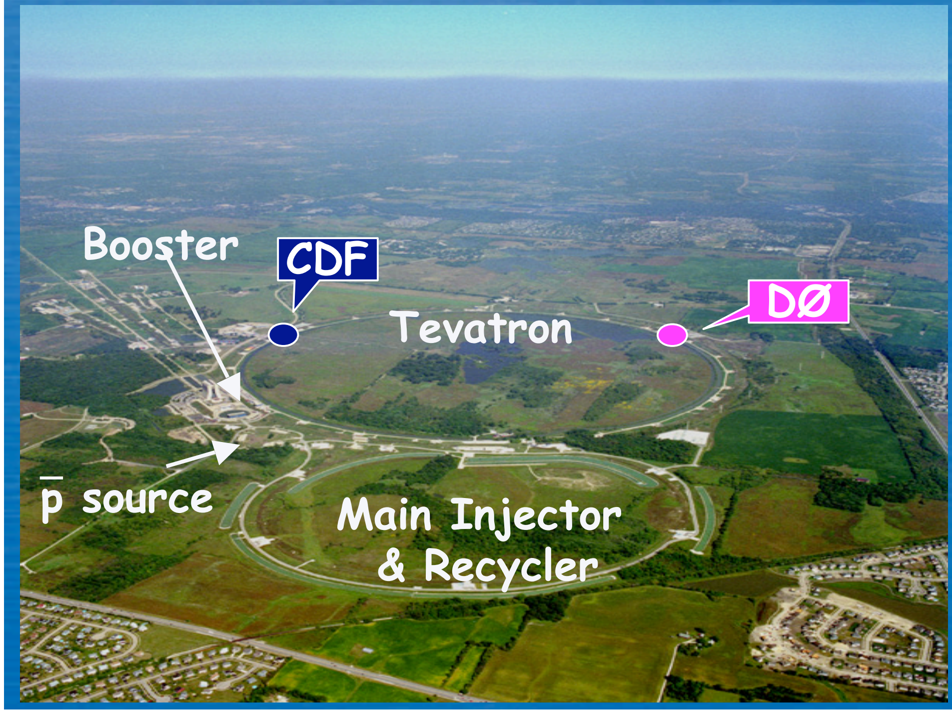
- Bs Mixing
    - For Flavor Tagging calibration to be used in $B_s \to J/\psi\varphi$

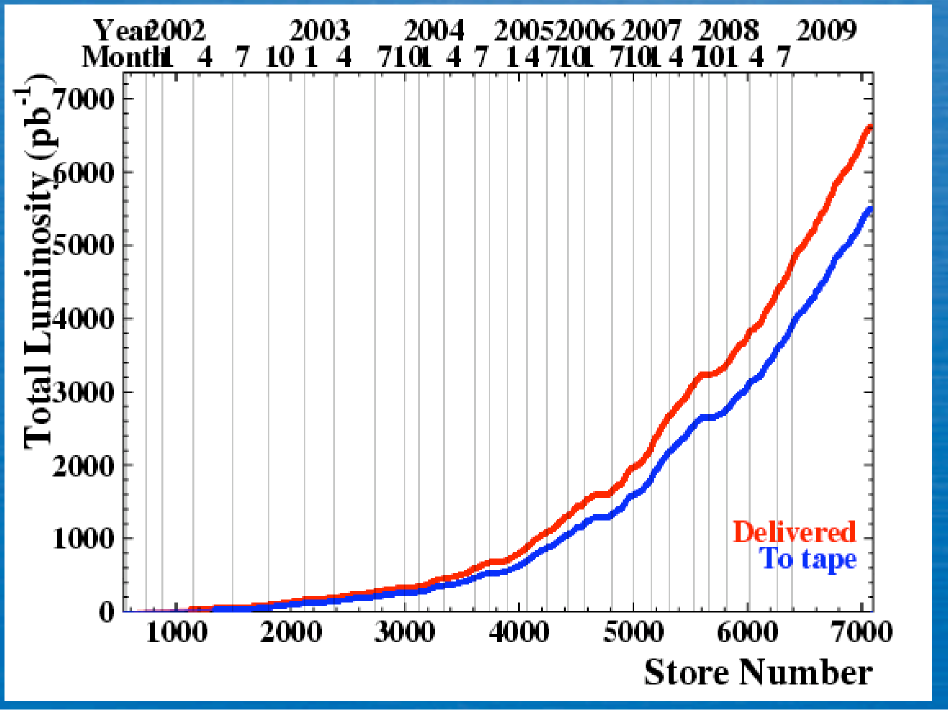
Tevatron at Fermilab

- $p\bar{p}$ collisions at 1.96 TeV
- All b hadron species produced:

  B, B_s, B_c, Λ_b, Σ_b, Ξ_b, Ω_b...

- more than 5 fb^{-1} data on tape for each experiment
- Show analyses ≤ 2.8 fb^{-1} of data





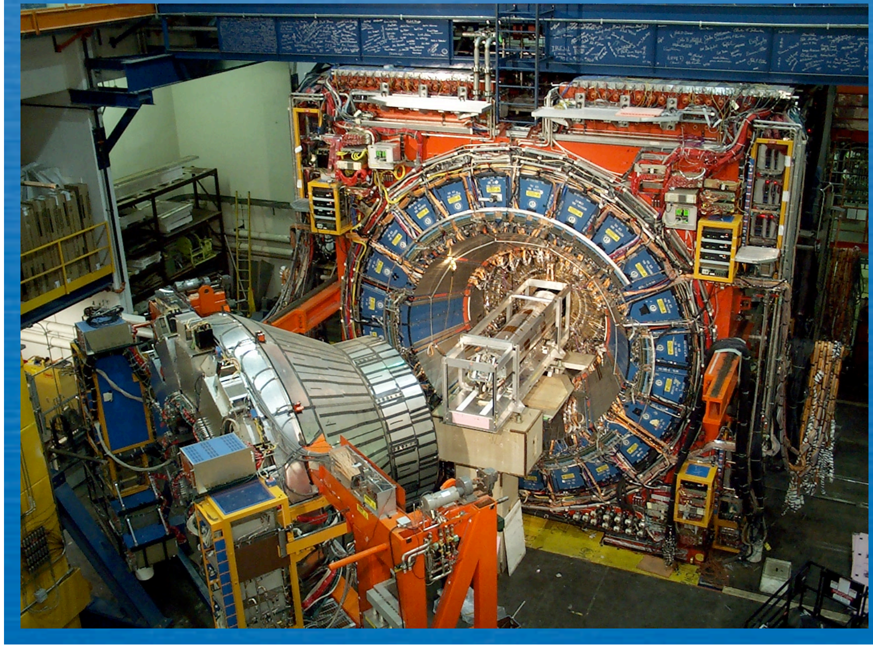
CDF II Detector

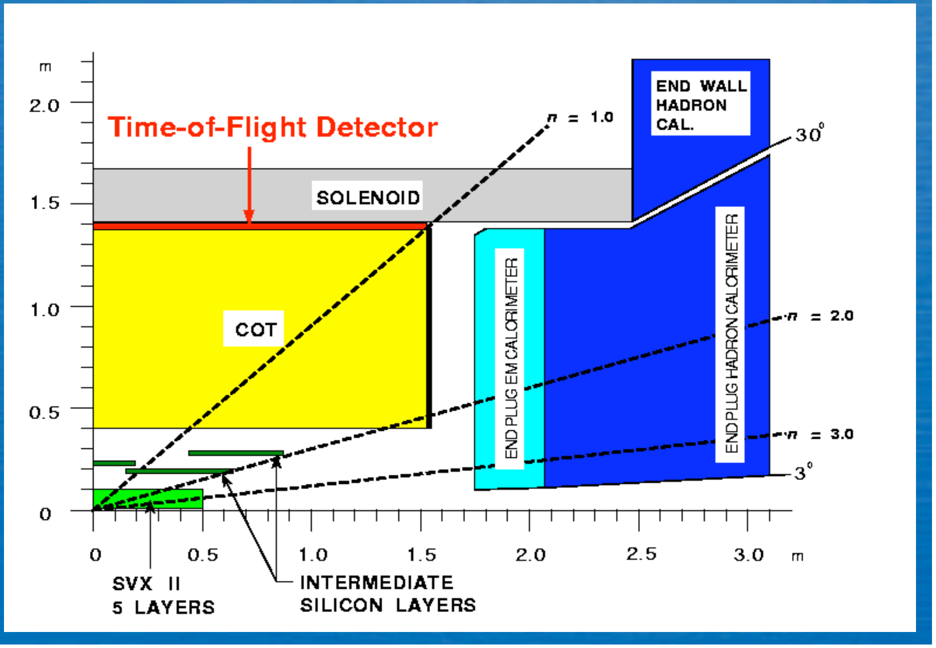
TRACKING system:

- Drift Chamber 96 layers ($|\eta|<1$)
  particle ID with dE/dx
- Silicon Tracker (L00+SVX+ISL, up to $|\eta|\approx 2$)
  I.P. resolution 35 μm at 2 GeV

In Addition:

- Particle identification: dE/dX and TOF
- Electron and muon ID by calorimeters and muon chambers





Neutral B_s System

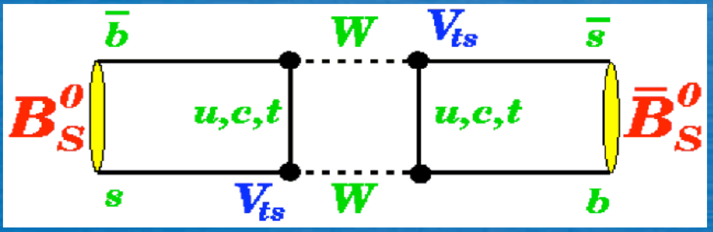
- Time evolution of B_s flavor eigenstates described by Schrodinger equation:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix} = H \begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix} \equiv \Bigg[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2} \underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}} \Bigg] \begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix}$$

- Diagonalize mass (M) and decay (Γ) matrices
  → mass eigenstates :

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle \qquad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$

- Flavor eigenstates differ from mass eigenstates and mass eigenvalues are different ($\Delta m_s = m_H - m_L \approx 2|M_{12}|$)



- Mass eigenstates have different decay widths
  $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\Phi_s)$ where $\phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4\text{x}10^{-3}$

$\Delta\Gamma$: Lifetime Difference

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

CP Specific: Bs → DsDs

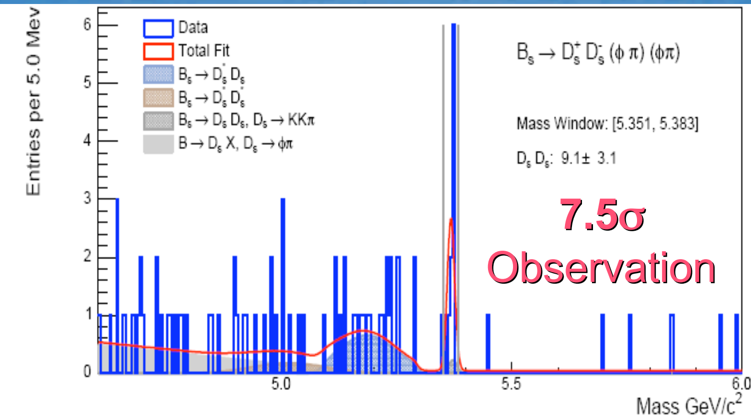
- Assume no CP violation: B_s^L = CP even, B_s^H = CP odd
- b → ccs decay (e.g. Bs → Ds Ds) is pure CP even
- Thus a lifetime measurement of Bs → Ds Ds would measure Γ_L

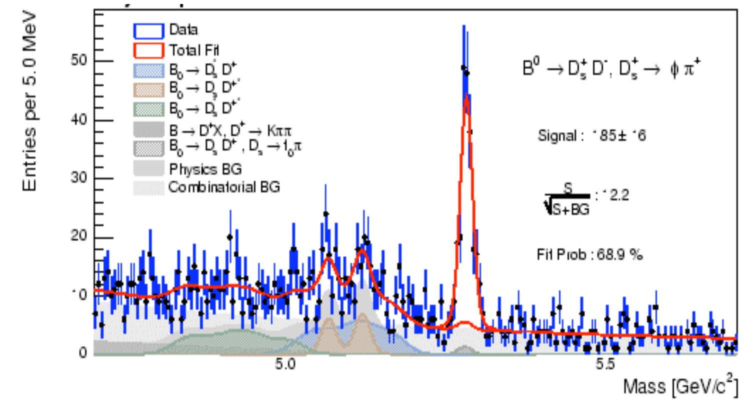
HOWEVER

- Branching ratio is related to $\Delta\Gamma/\Gamma$ and if neglect small CP odd component:

$$\frac{\Delta\Gamma}{\Gamma} = 2Br\left(B_s^0 \rightarrow D_s^{(*)-} D_s^{(*)+}\right)$$

- BR ($B_s \rightarrow D_s\, D_s$) measured relative to $B^0 \rightarrow D_s\, D^-$
- Three D_s decay modes reconstructed in each case





In 355 pb^{-1}

$$\frac{BR(B_s^0 \rightarrow D_s D_s)}{BR(B_d^0 \rightarrow D_s D^-)} = 1.44^{+0.38}_{-0.31}(stat)^{+0.08}_{-0.12}(sys) \pm 0.21\left(\frac{f_s}{f_d}\right) \pm 0.20(BR)$$

CP Specific: Bs → DsDs

With 355 pb^{-1} ⟶ 95% C.L.: $\frac{\Delta\Gamma}{\Gamma} \geq 2Br\left(B_s^0 \to D_s^{(*)-} D_s^{(*)+}\right) \geq 0.012$

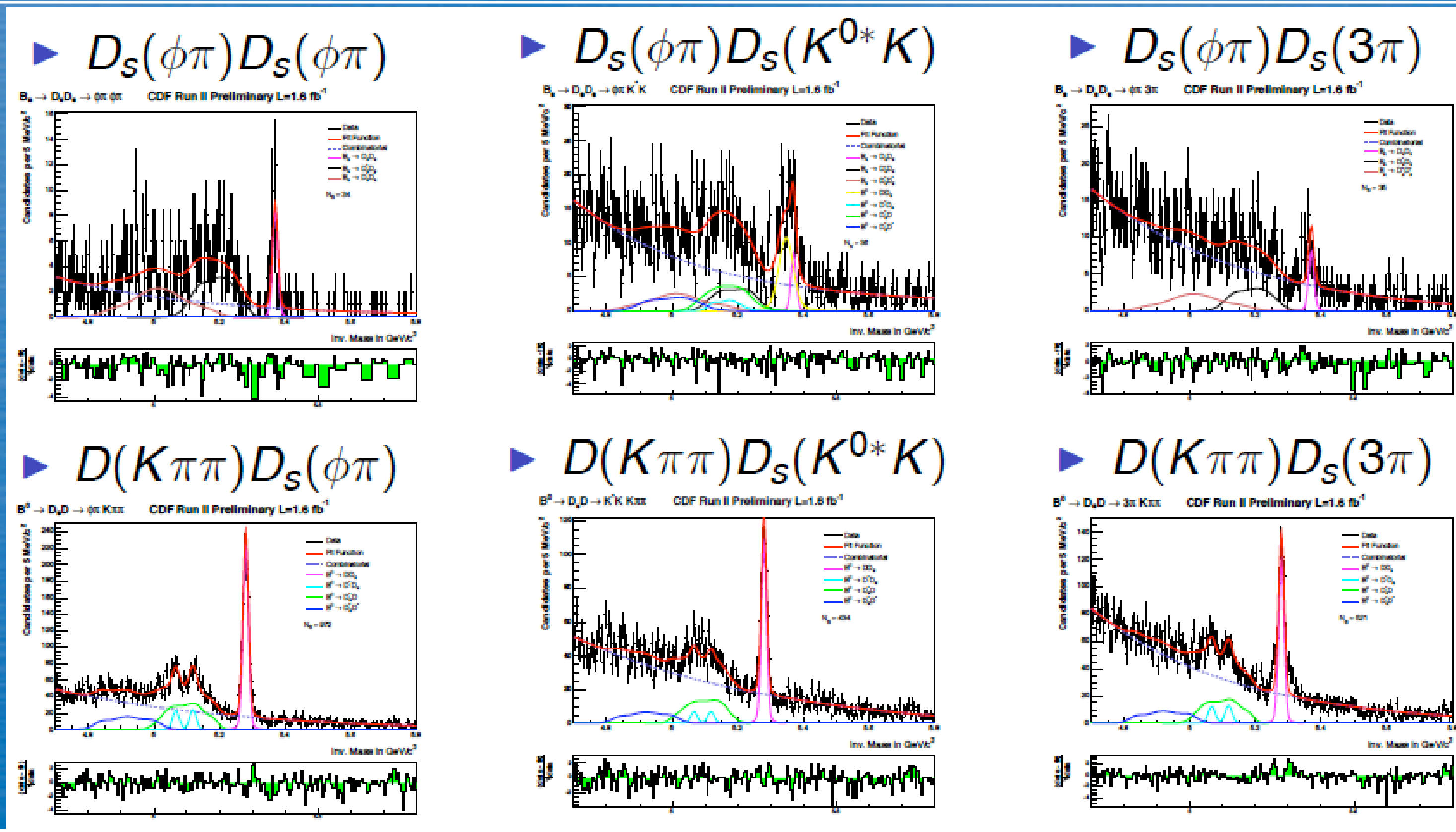
Phys.Rev.Lett.100:021803,2008.

- New Analysis on going.

- New Neural Network Selection to increase acceptance (in 1.6 fb^{-1}):

~ 105 Bs→DsDs

~ 1930 Bd→DDs



CP Specific: Bs → KK

- First Measurement of Bs → KK lifetime performed in 360 pb^{-1}. Bs → KK extracted using a Maximum Likelihood fit that combines kinematics and particle identification information
- Lifetime measurement interesting since ~ 95% CP even
- B→hh decays can be resolved at CDF
  - Displaced track trigger
  - Good mass resolution

$\tau(B_s \rightarrow K^+K^-) = 1.53 \pm 0.18(stat) \pm 0.02(sys)$ ps

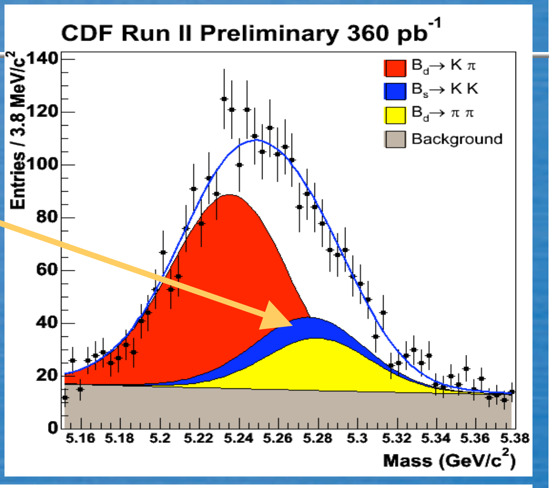
Use HFAG flavour specific $\tau = 1.454 \pm 0.040$ ps

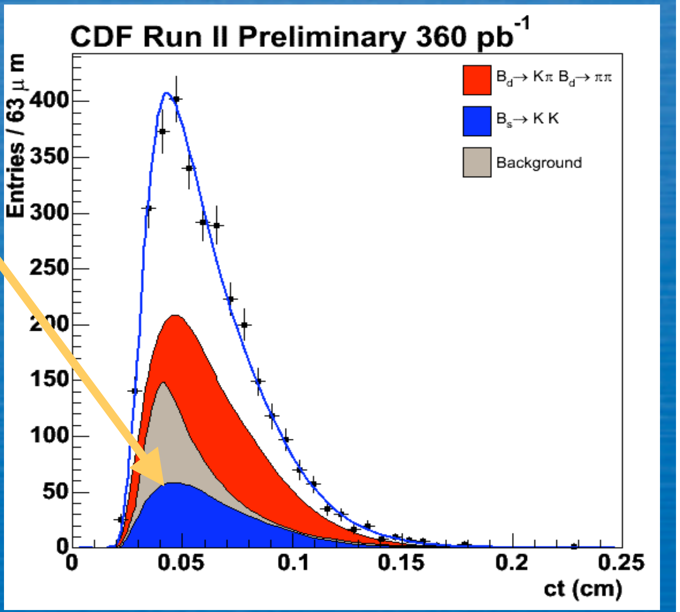
360 pb^{-1}

$$\frac{\Delta\Gamma}{\Gamma} = -0.08 \pm 0.23(stat) \pm 0.03(sys)$$

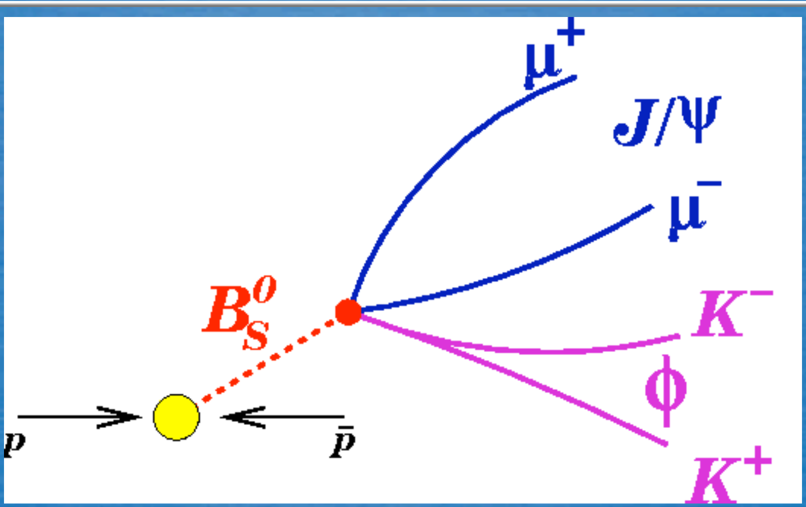
http://www-cdf.fnal.gov/physics/new/bottom/060126.blessed-BsKK_lifetime/

In 2fb^{-1} we expect:
τ stat error 0.06-0.09ps

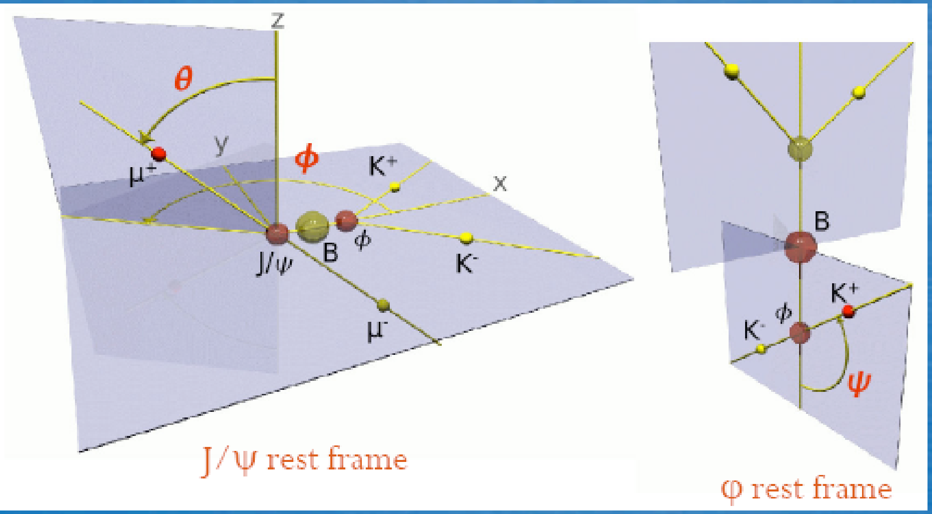




$Bs \rightarrow J/\psi\phi$



- three decay angles $\vec{\rho} = (\theta,\phi,\psi)$ describe directions of final decay products



- Extremely physics rich decay mode

- Can measure lifetime, decay width difference $\Delta\Gamma$ and CP violating phase β_s

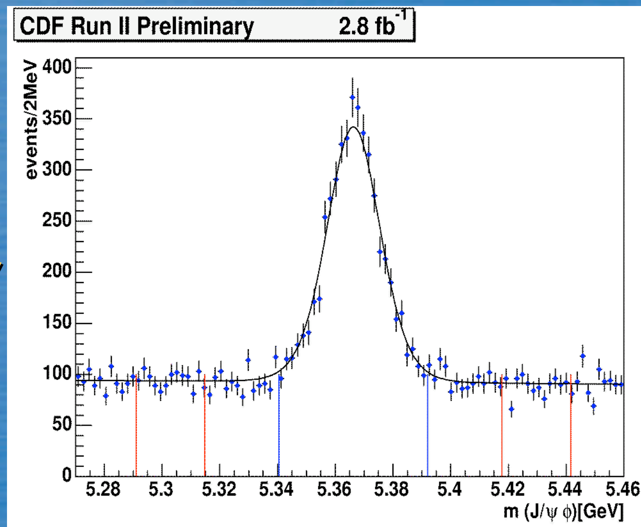
- Decay of B_s (spin 0) to J/Ψ(spin 1) Φ(spin 1) leads to three different angular momentum final states:

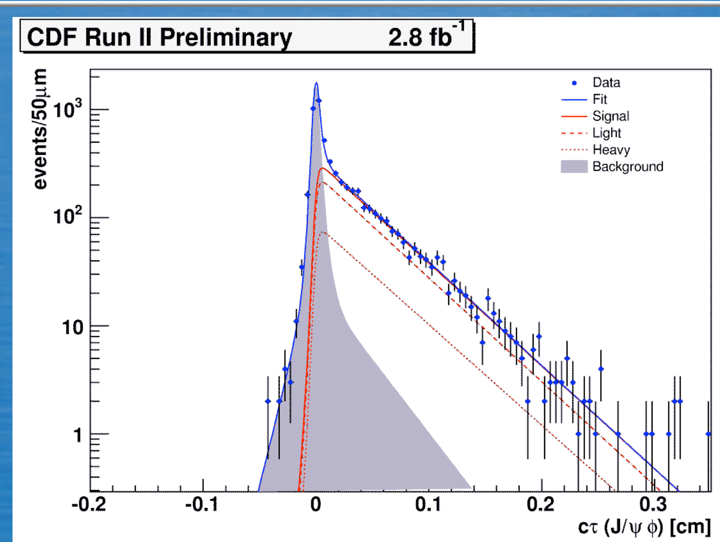
L = 0 (s-wave), 2 (d-wave) → CP even (≈ short lived or light B_s if $\Phi_s \approx 0$)

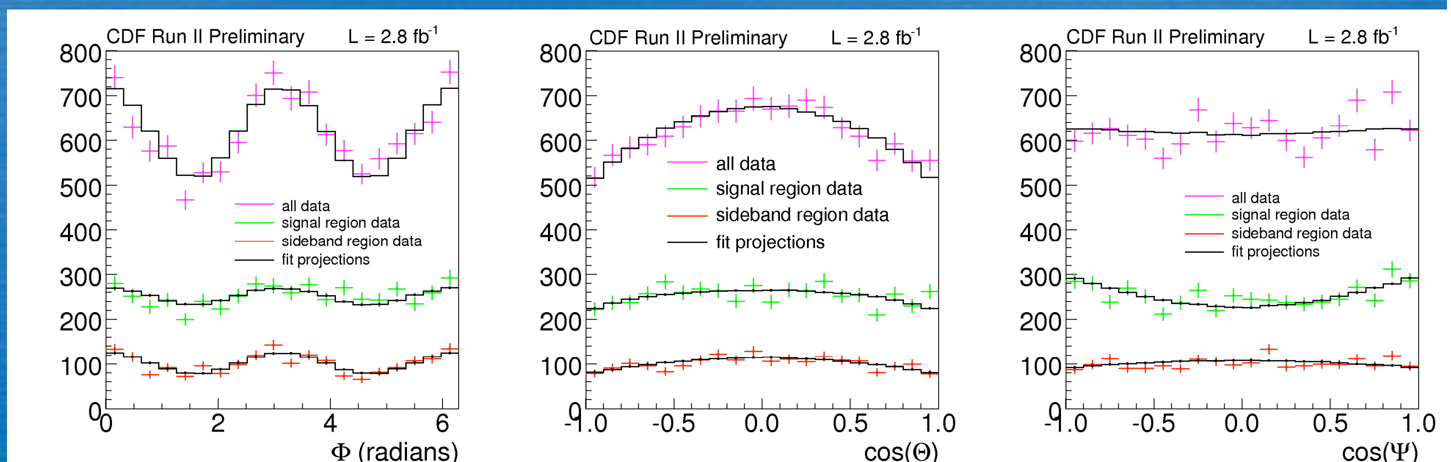
L = 1 (p-wave) → CP odd (≈ long lived or heavy B_s if $\Phi_s \approx 0$)

Tagged Bs → J/ψφ: ΔΓ

- Performed simultaneous mass, lifetime and angular fit
- CDF reconstructed around 3200 events in 2.8 fb^{-1} using selections based on Neural Network .







Tagged Bs $\rightarrow J/\psi\phi$: $\Delta\Gamma$

Assume No CP violation
In 2.8 fb^{-1} :

$c\tau_s$ = 459 ± 12 (stat) ± 3 (sys) μm

$\Delta\Gamma$ = 0.02 ± 0.05 (stat) ± 0.01 (sys) ps^{-1}

$|A_0|^2$ = 0.508 ± 0.024 (stat) ± 0.008 (sys)

$|A_{//}|^2$ = 0.241 ± 0.019 (stat) ± 0.007 (sys)

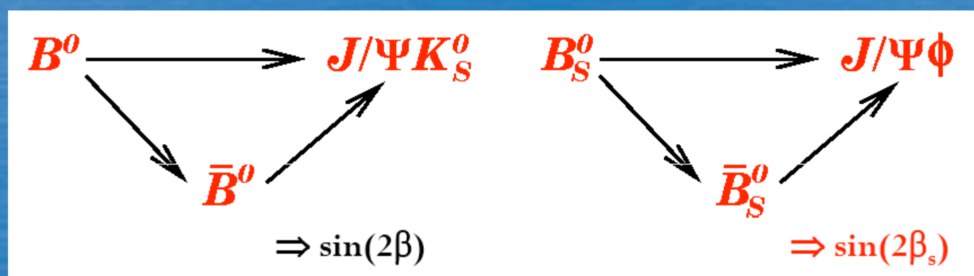
Predicted $\Delta\Gamma$
0.096± 0.039ps^{-1}
(arxiv: 0802.0977)

This result with 2.8 fb^{-1} :
http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/

Published analysis with 1.7fb^{-1} : Phys. Rev. Lett. 100, 121803 (2008)

Add Flavor Tagging

CP Violation Phase β_s in $B_s \to J/\psi\phi$



$$\beta_s^{SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- CP violation phase β_s in SM is predicted to be very small, $O(\lambda^2)$
→ New Physics CPV can compete or even dominate over small Standard Model CPV

- Ideal place to search for New Physics

CP Violation Phase β_s in Tagged $B_s \rightarrow J/\psi\phi$

- Likelihood expression predicts better sensitivity to β_s but still double minima
due to symmetry:

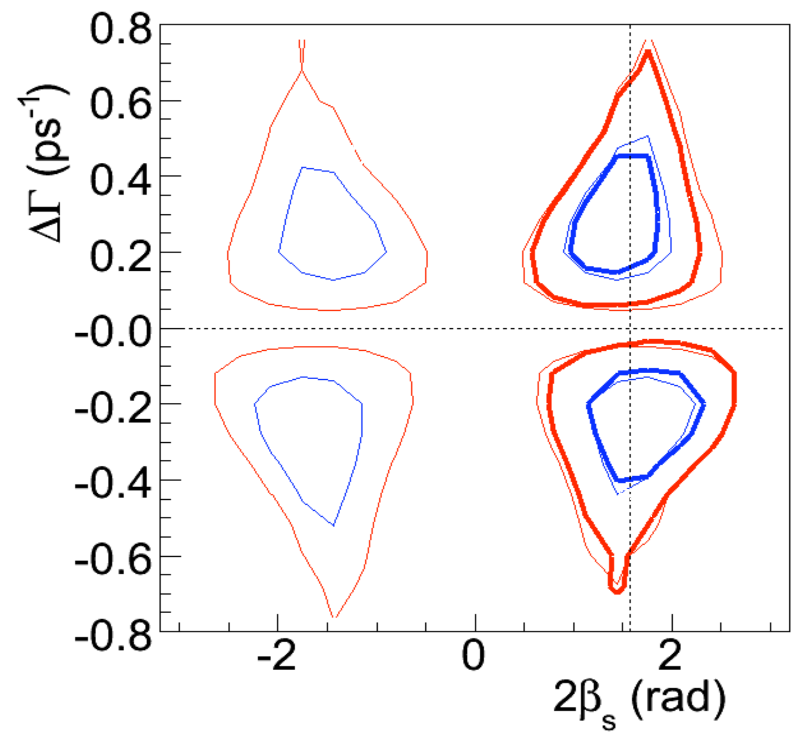
$$2\beta_s \to \pi - 2\beta_s$$
$$\Delta\Gamma \to -\Delta\Gamma$$
$$\delta_{\parallel} \to 2\pi - \delta_{\parallel}$$
$$\delta_{\perp} \to \pi - \delta_{\perp}$$

- Study expected effect of tagging using pseudo-experiments

- Improvement of parameter resolution is small due to limited tagging power ($\varepsilon D^2 \sim 4.5\%$ compared to B factories ~30%)

- However, $\beta_s \to -\beta_s$ no longer a symmetry
→ 4-fold ambiguity reduced to 2-fold ambiguity
→ allowed region for β_s is reduced to half

pseudo experiment $2\beta_s$-$\Delta\Gamma$ likelihood profile



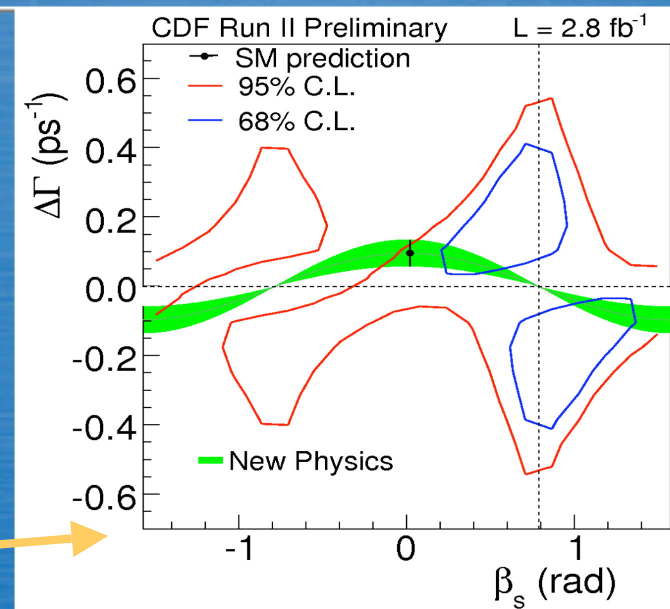
strong phases can separate the two minima

$2\Delta\log(L) = 2.3 \approx 68\%$ CL
$2\Delta\log(L) = 6.0 \approx 95\%$ CL

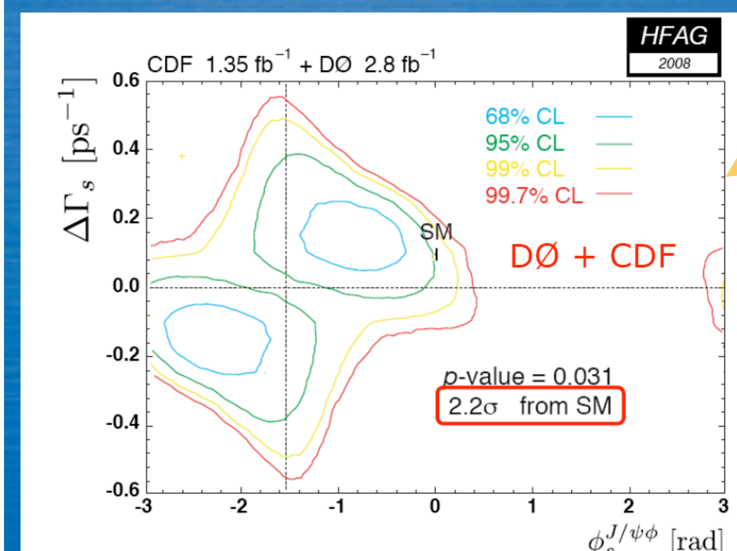
un-tagged
tagged

CP Violation Phase β_s in Tagged $B_s \rightarrow J/\psi\phi$

- CDF: Standard Model probability 7%, ~1.8σ



- HFAG combines old CDF (1.4 fb^{-1}, 1.5 σ from SM, PRL 100, 161802 (2008))
- DØ (2.8 fb^{-1}, 1.7 σ from SM) results yield a 2.2 σ deviation from SM (similar results from UTFit and CKM)



Different Conventions:

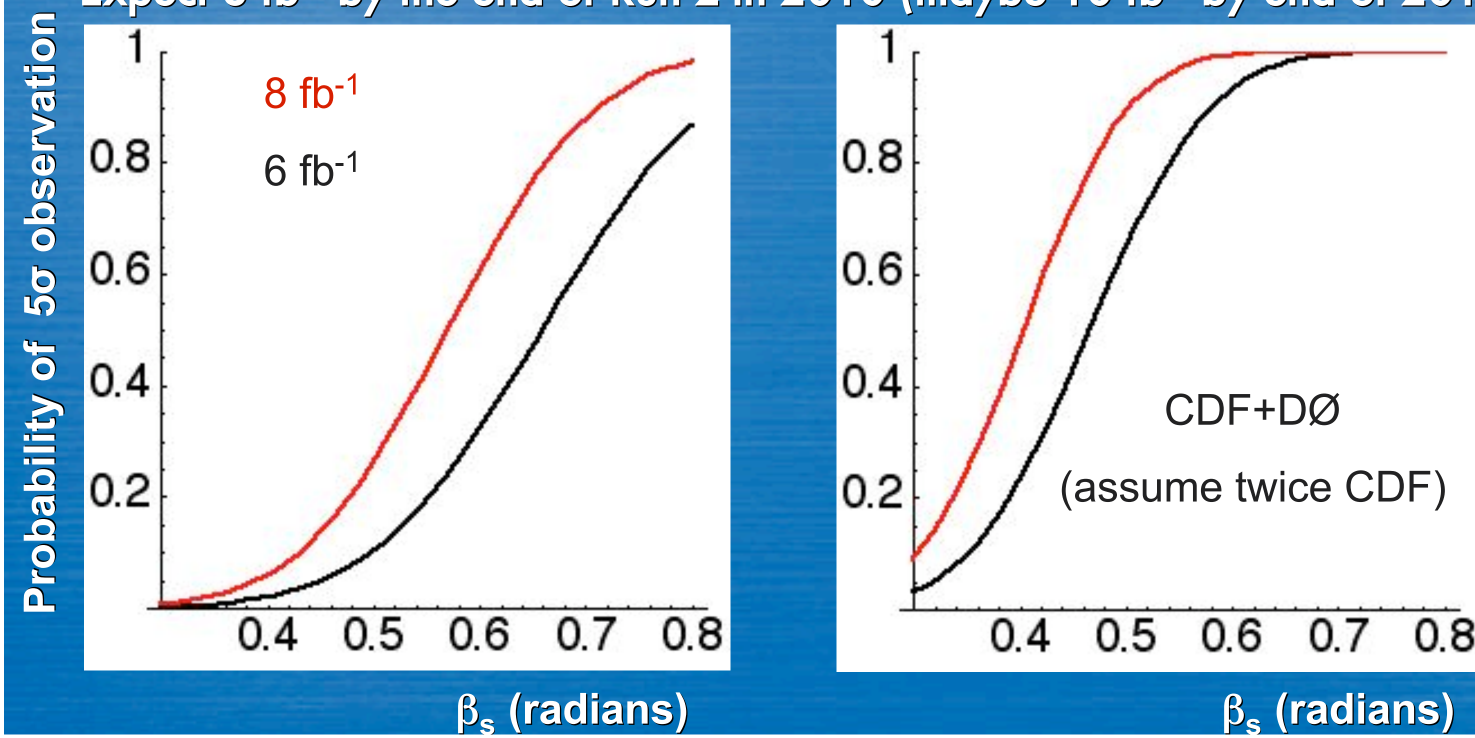
ϕ_s β_s

- Ongoing CDF and DØ work to produce Tevatron $\Delta\Gamma$ - β_s average using 2.8 fb^{-1}

- Investigating two combination methods:
  - combine 2D profile likelihoods
    - will be ready very soon
  - perform simultaneous fit of CDF and DØ data
    - expect to be more powerful, longer timescale

Future

- Tevatron can search for anomalously large values of β_s .
- Shown results with 2.8 fb^{-1}, but more than 5 fb^{-1} already on tape to be analyzed soon with NEW flavor tagger.
- Currently considering other improvements.
- Expect 8 fb^{-1} by the end of Run 2 in 2010 (maybe 10 fb^{-1} by end of 2011 ?).



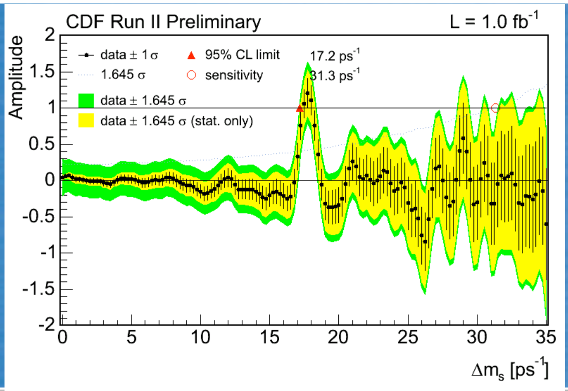
If β_s is indeed large combined Tevatron results have good chance to prove it.

B_s Mixing

CDF Observed Bs Mixing and Measured :

$\Delta m_s = 17.77 \pm 0.12\ ps^{-1}$

PRL 97, 242003 2006

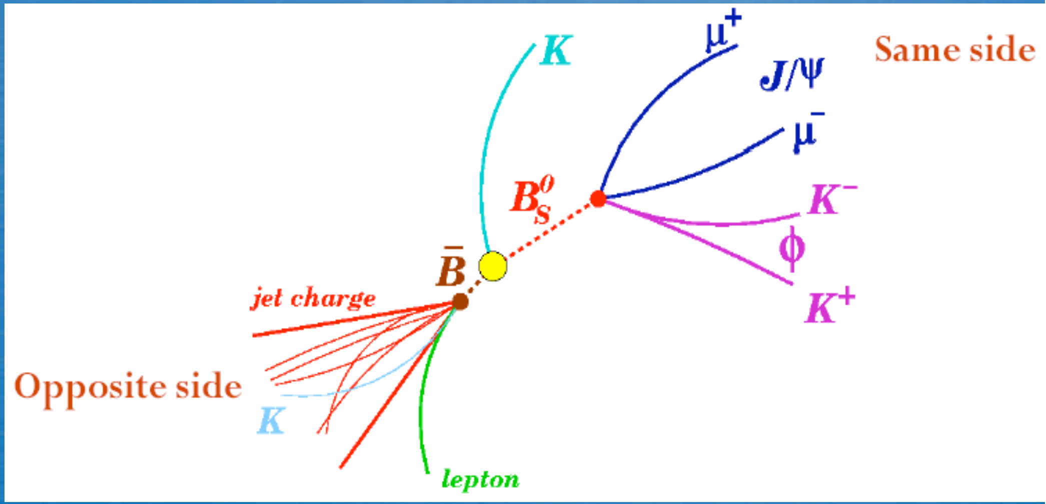


Bs Mixing is now a very important benchmark for flavor tagging calibration

- Tevatron: *b*-quarks mainly produced in *b anti-b*-pairs→ flavor of the B meson at production inferred with

- OST: exploits decay products of other *b*-hadron in the event

- SST: exploits the correlations with particles produced in fragmentation

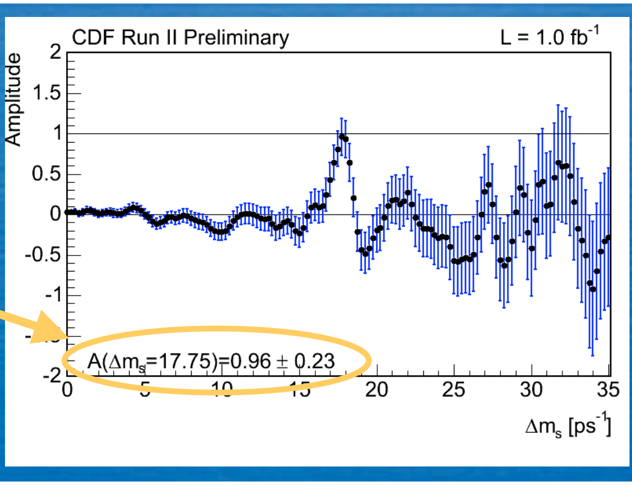


Old Tagger

- OST calibrated on *data* (B^+, B^0)

- SSKT calibrated on MC, but checked on B_s mixing measurement

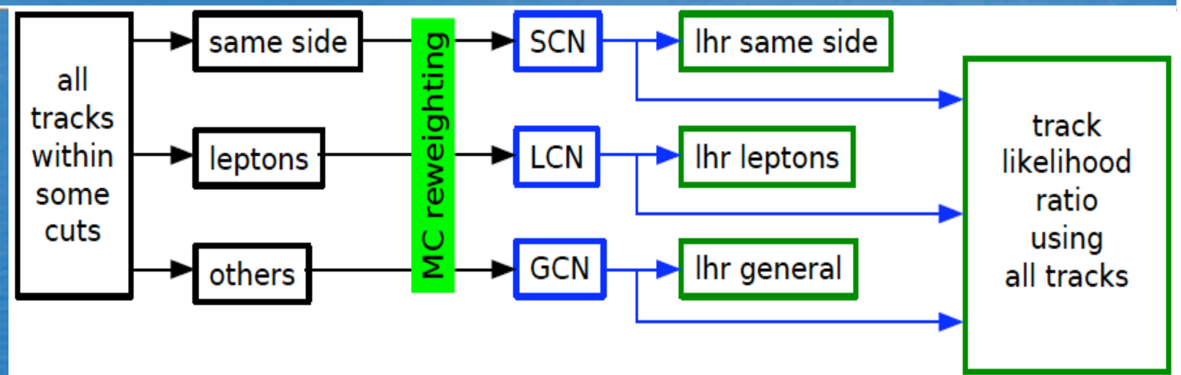
- Combined tagging power at CDF ~4.5% (compared to ~30% at B factories)



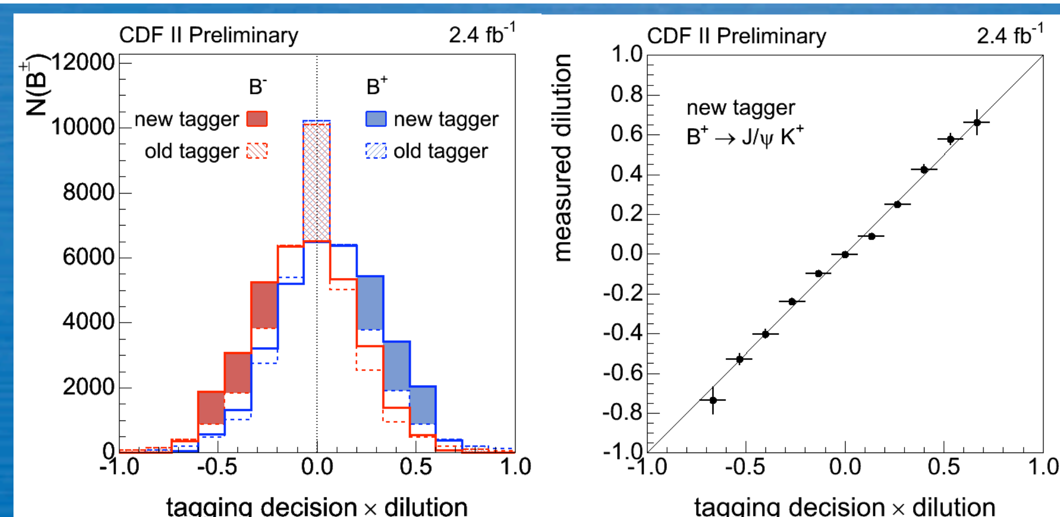
18 New Tagger Principle

Combine the information from all tracks in the event

- **Same Side:** tracks in the same side in which the same side B was found.
- **Leptons:** tracks that are electron or muon candidate.
- **Others:** al remaining tracks (very low B flavor information).



- **Split** all charged tracks into the three subsamples: **same side, leptons and others.**
- **Train** an independent **"Track Flavor Correlation Neural Network"** for each subsample
- **Combine** tracks of each subsample in a **separate Likelihood Ratio**



The new Tagger will be calibrated/checked on MC and on **NEW B_s mixing measurement** with higher statistics data samples and used in **NEW tagged $B_s \rightarrow J/\psi\phi$**

Conclusions

- Several ways of measuring $\Delta\Gamma$ have been deployed; to be updated soon:

$$\Delta\Gamma(B_s \to J/\psi\phi) = 0.02 \pm 0.05(stat) \pm 0.01(sys)\, ps^{-1}$$

$$\frac{\Delta\Gamma}{\Gamma}(B_s \to K^+K^-) = -0.08 \pm 0.23(stat) \pm 0.03(sys)$$

$$\frac{\Delta\Gamma}{\Gamma} \geq 2Br\left(B_s^0 \to D_s^{(*)-} D_s^{(*)+}\right) \geq 0.012$$

(95% C.L.)

- Significant regions in β_s space are ruled out
- CDF observes 1,8 sigma β_s deviations from SM predictions
- Combined HFAG result 2.2 sigma w.r.t SM expectation
- Soon: updated analyses from CDF with new tagger and more data

Backup Slides

$B_s \to J/\Psi\Phi$ Decay Rate

- $B_s \to J/\Psi\Phi$ decay rate as function of time, decay angles and initial B_s flavor:

$$\frac{d^4P(t,\vec{\rho})}{dtd\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho})$$
$$+ |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp|\mathcal{U}_+ f_4(\vec{\rho})$$
$$+ |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp|\mathcal{V}_+ f_6(\vec{\rho}),$$

time dependence terms

angular dependence terms

terms with β_s dependence

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)$$
$$\mp \eta\sin(2\beta_s)\sin(\Delta m_s t)],$$

terms with Δm_s dependence present if initial state of B meson (B vs anti-B) is determined (flavor tagged)

$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t)$$
$$- \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t)$$
$$\pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)].$$

'strong' phases:

$$\delta_\parallel \equiv \mathrm{Arg}(A_\parallel(0)A_0^*(0))$$
$$\delta_\perp \equiv \mathrm{Arg}(A_\perp(0)A_0^*(0))$$

Analysis without Flavor Tagging

- Drop information on production flavor
- Simpler but less powerful analysis

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \mp \cancel{\eta\sin(2\beta_s)\sin(\Delta m_s t)}],$$

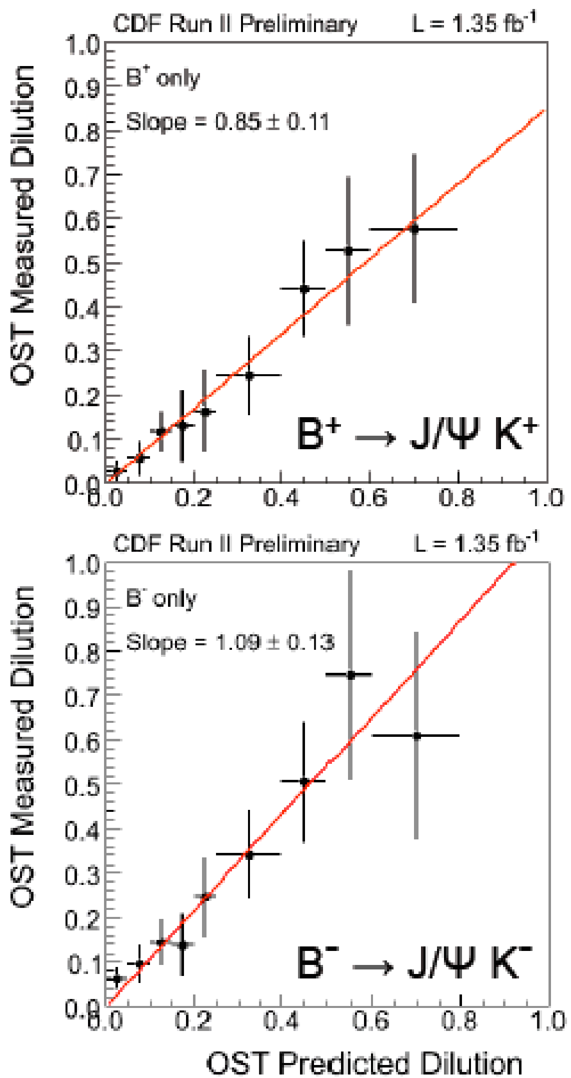
$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times [\cancel{\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)} - \cancel{\cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t)} \pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

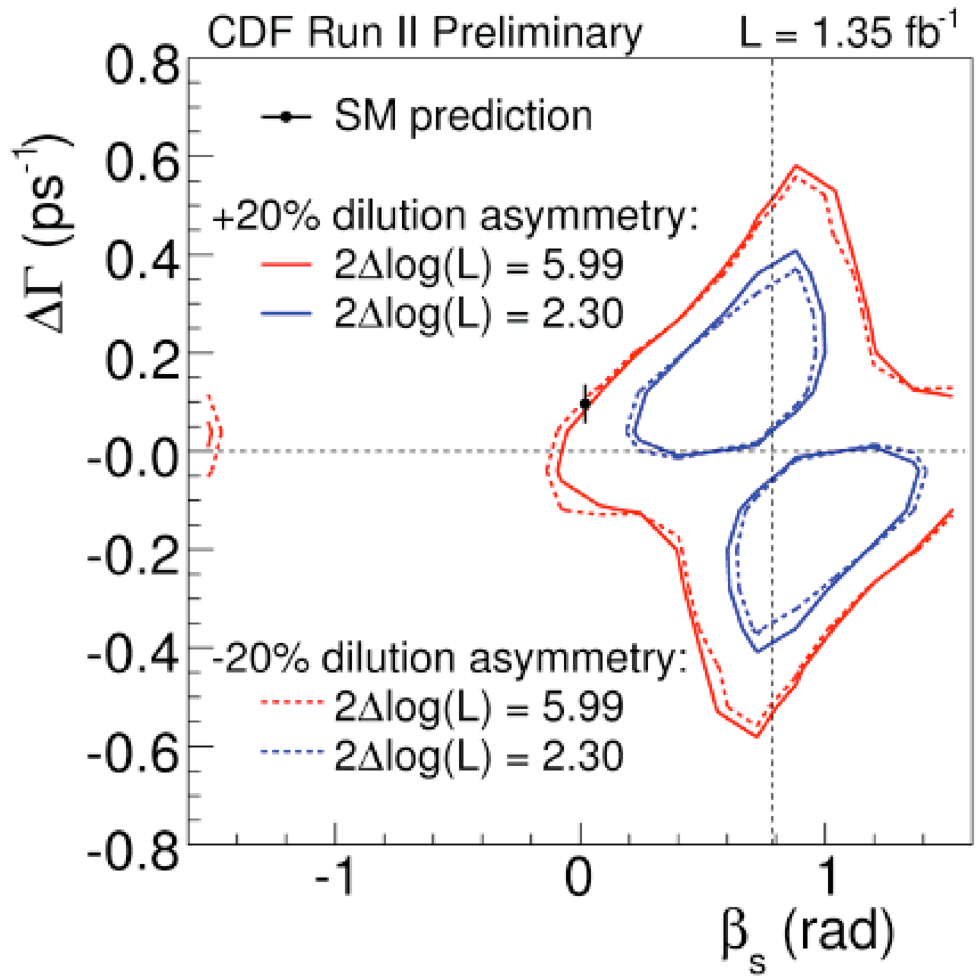
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\cancel{\sin(\delta_\perp)\cos(\Delta m_s t)} - \cancel{\cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t)} \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)] .$$

- Still sensitive to CP-violation phase β_s
- Suited for precise measurement of width-difference and average lifetime

Effect of Dilution Asymmetry on β_s

- Effect of 20% b-bbar dilution asymmetry is very small





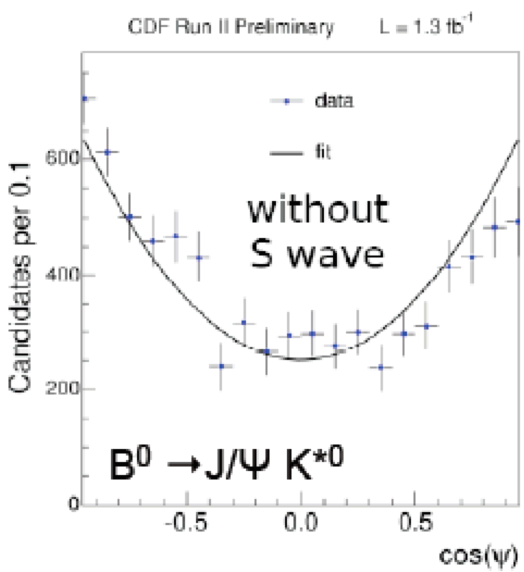
S-wave Effect on Measurement of CP Violating Phases ?

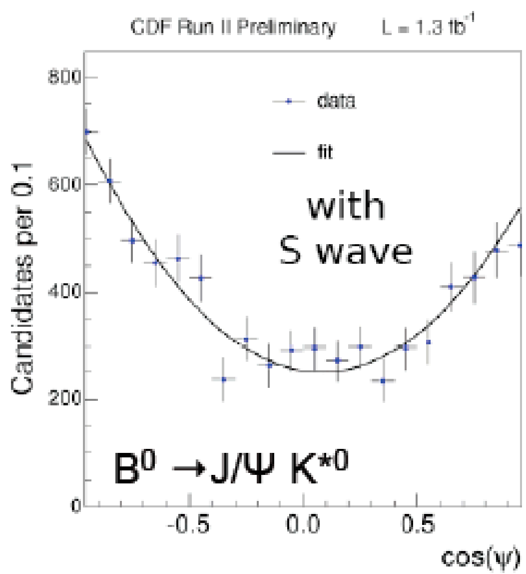
S.Stone, L.Zhang, arXiv:0812.2832

- What is effect of interference between S-wave $B_s \rightarrow J/\Psi\ f^0$ or $B_s \rightarrow J/\Psi\ K^+K^-$ (non-resonant) and $B_s \rightarrow J/\Psi\ \Phi$?

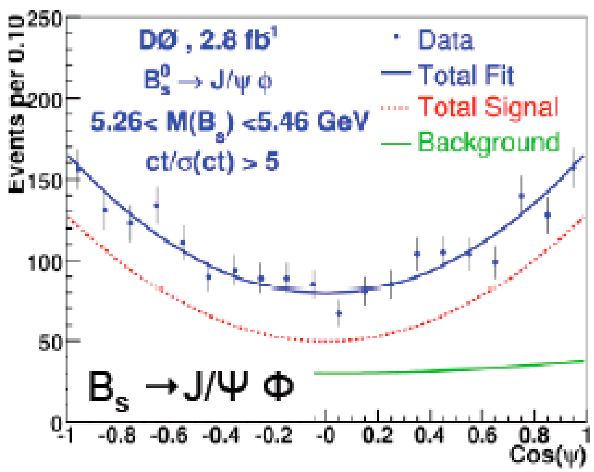
- Within statistics, no evidence for f^0 or non-resonant KK S-wave in Φ(KK) mass distribution

- cos(Ψ) distribution sensitive to S-wave interference:





Evidence for S-wave in $B^0 \rightarrow J/\Psi\ K^{*0}$

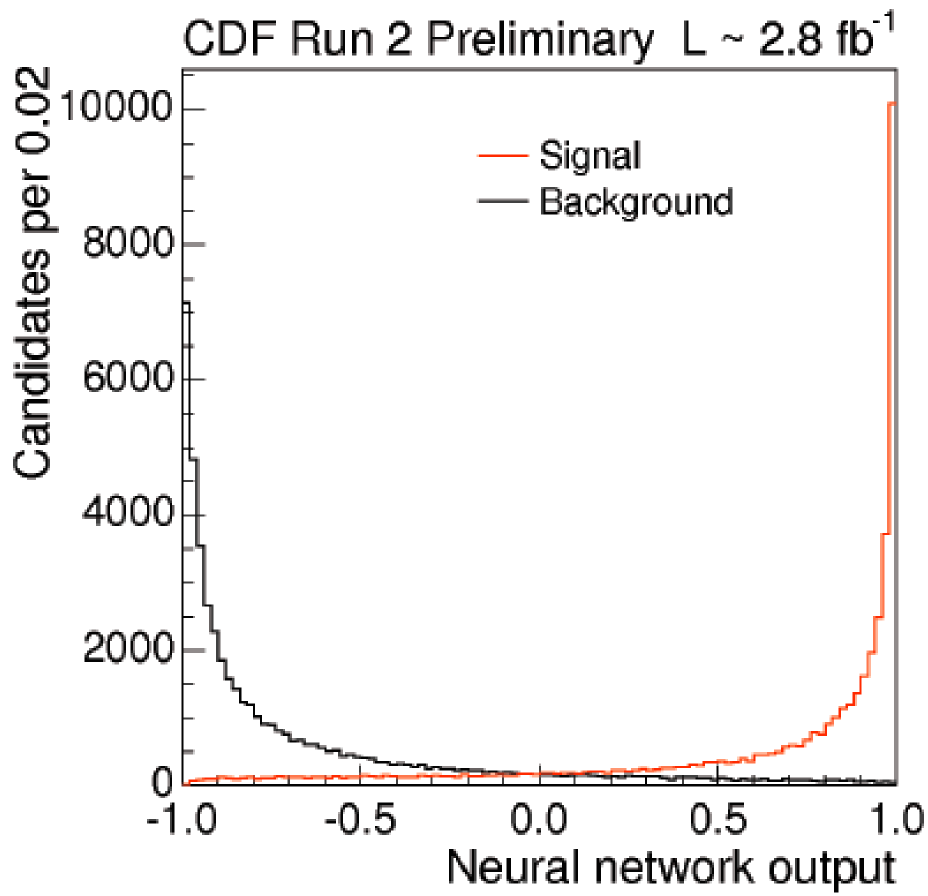


No evidence for S-wave in $B_s \rightarrow J/\Psi\ \Phi$

CDF Selection of B_s Signal Using ANN

- NN maximizes $S/\sqrt{(S+B)}$, trained on MC for signal and mass sidebands for background

- Variables used by NN
- B^0_s : use p_T and vertex quality
- J/ψ : use p_T and vertex prob.
- Φ : use mass and vertex quality
- PID (dE/dx + TOF) for Kaons from Φ
- …



CDF Cross-check on $B^0 \rightarrow J/\Psi K^{*0}$

$B^0 \rightarrow J/\psi K^{*0}$: high-statistics test of angular efficiencies and fitter

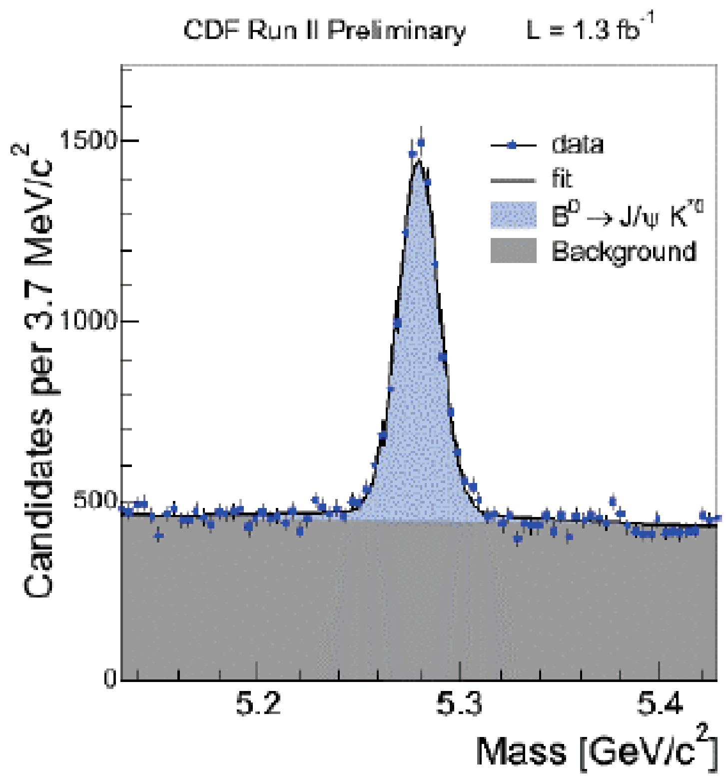
$c\tau = 456 \pm 6\ (\text{stat}) \pm 6\ (\text{syst})\ \mu\text{m}$

$|A_0(0)|^2 = 0.569 \pm 0.009\ (\text{stat}) \pm 0.009\ (\text{syst})$

$|A_\parallel(0)|^2 = 0.211 \pm 0.012\ (\text{stat}) \pm 0.006\ (\text{syst})$

$\delta_\parallel = -2.96 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$

$\delta_\perp = 2.97 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})$



- Not only agree with latest BaBar results, (PRD 76,031102 (2007)) but also competitive

$|A_0(0)|^2 = 0.556 \pm 0.009\ (\text{stat}) \pm 0.010\ (\text{syst})$

$|A_\parallel(0)|^2 = 0.211 \pm 0.010\ (\text{stat}) \pm 0.006\ (\text{syst})$

$\delta_\parallel = -2.93 \pm 0.08\ (\text{stat}) \pm 0.04\ (\text{syst})$

$\delta_\perp = 2.91 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$

β_s vs ϕ_s

- Up to now, introduced two different phases:

$$\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4\times10^{-3} \qquad \text{and} \qquad \beta_s^{\mathrm{SM}} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$$

- New Physics can affect both phases by same quantity ϕ_s^{NP} (A. Lenz, arxiv:0705.3802v2):

$$2\beta_s = 2\beta_s^{\mathrm{SM}} - \phi_s^{\mathrm{NP}}$$

$$\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$$

- If the new physics phase ϕ_s^{NP} dominates over the SM phases $2\beta_s^{\mathrm{SM}}$ and ϕ_s^{SM}
→ neglect SM phases and obtain:

$$2\beta_s = -\phi_s^{\mathrm{NP}} = -\phi_s$$

β_s Phase and the CKM Matrix

- CKM matrix connects mass and weak quark eigenstates
- Expand CKM matrix in $\lambda = \sin(\theta_{Cabibbo}) \approx 0.23$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

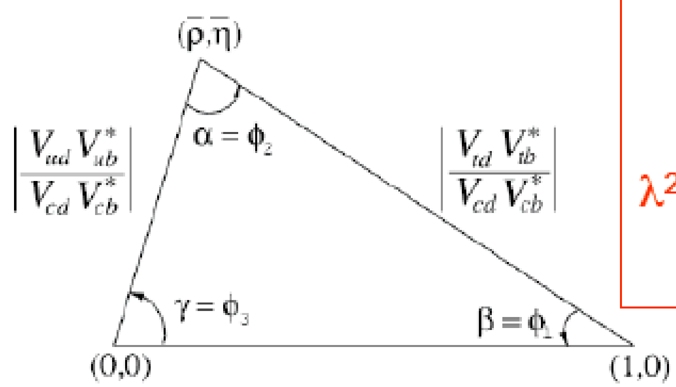
- To conserve probability CKM matrix must be unitary
  → Unitary relations can be represented as "unitarity triangles"

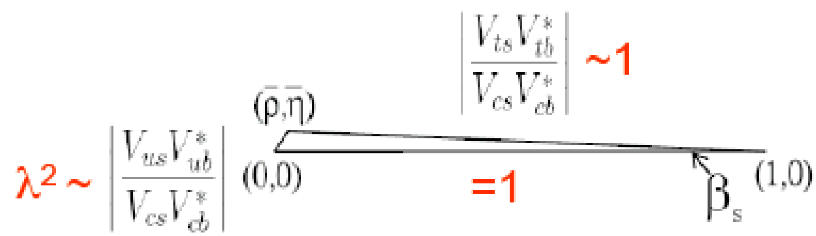
unitarity relations:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

unitarity triangles:





very small CPV phase β_s of order λ^2 accessible in B_s decays